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# CONTROL ROD WORTH EVALUATION OF TRIGA MARK II REACTOR

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## ABSTRACT

In this paper, KENOV.a module of SCALE code system was used to perform Monte Carlo simulation of the TRIGA MARK II research reactor benchmark experiments [1,2] in steady state operation conditions. Robert Jeraj and his coworkers have presented a similar simulation of the TRIGA MARK II research reactor benchmark experiments via MCNP4A in 1997. [3]

The core excess reactivity measurement experiments were simulated using detailed geometrical representation with ENDF/B-V 44 and 238 group cross-section libraries. The experiments on control rod worth measurements were simulated for rod insertion and rod exchange method. It was shown that the experimental results on control rod worths are in good agreement with KENOV.a simulations in the case of rod insertion method. However, the simulation results for the rod exchange method are not in agreement with the experimental data since the model used in KENOV.a does not represent the experimental setup.

## 1 INTRODUCTION

In small research reactors, reactivities and reactivity increments play an important role in reactor physics, safety, control and operational schedules. There are several experimental techniques used to measure the reactivities. These methods can be dynamic or static, and the experimental measurements could be used as a set of benchmark cases in the verification of neutronic codes. And, one of the parameter for the safety evaluations of research reactors is the rod worth of control element.

There are various experimental techniques used for the measurements of rod worth. First set of detailed experimental measurements on TRIGA Mark II research reactor in Ljubljana was given by Irena Mele et.al., in 1993 [1] and [2]. These experiments were performed as part of the start-up tests and play an important role as benchmark experiments for small research reactor neutronic code performance evaluation and validation. In the study of Robert Jeraj and his coworkers, a detailed Monte Carlo simulation of the TRIGA Mark II benchmark experiments via MCNP4A Monte Carlo code was presented.

The purpose of this study is to perform Monte Carlo simulation of the benchmark experiments of Triga Mark II research reactor utilizing KENOV.a module of SCALE code system. In particular, simulation of the TRIGA Mark II research reactor benchmark experiments referred in [1] and [2] was presented and the simulation results were compared with the Monte Carlo simulation results given in [3].

Moreover, full core normalised fission density distribution was obtained for each core configuration. We also demonstrate that, the rod worth calculations depend on the configuration of the reactor and the measurement techniques used in the experiments.

The outline of the paper is as follows. In section 2, we give detailed core geometry and material properties used in the simulation. In section 3, the criticality simulation result of each core configuration was given. Rod insertion and rod exchange experiments were simulated and the results compared with the experimental and the simulation results given in [1], [2] and [3]. The last section is devoted for conclusion and future work.

## 2 CORE CONFIGURATIONS AND MATERIAL PROPERTIES

A more detailed description of TRIGA Mark II research reactor could be found in [1] and [2]. In the simulation via KENOV.a detailed core geometry was used for each core configuration. These core configurations denoted as 132, 133 and 134 are shown in Fig 1.

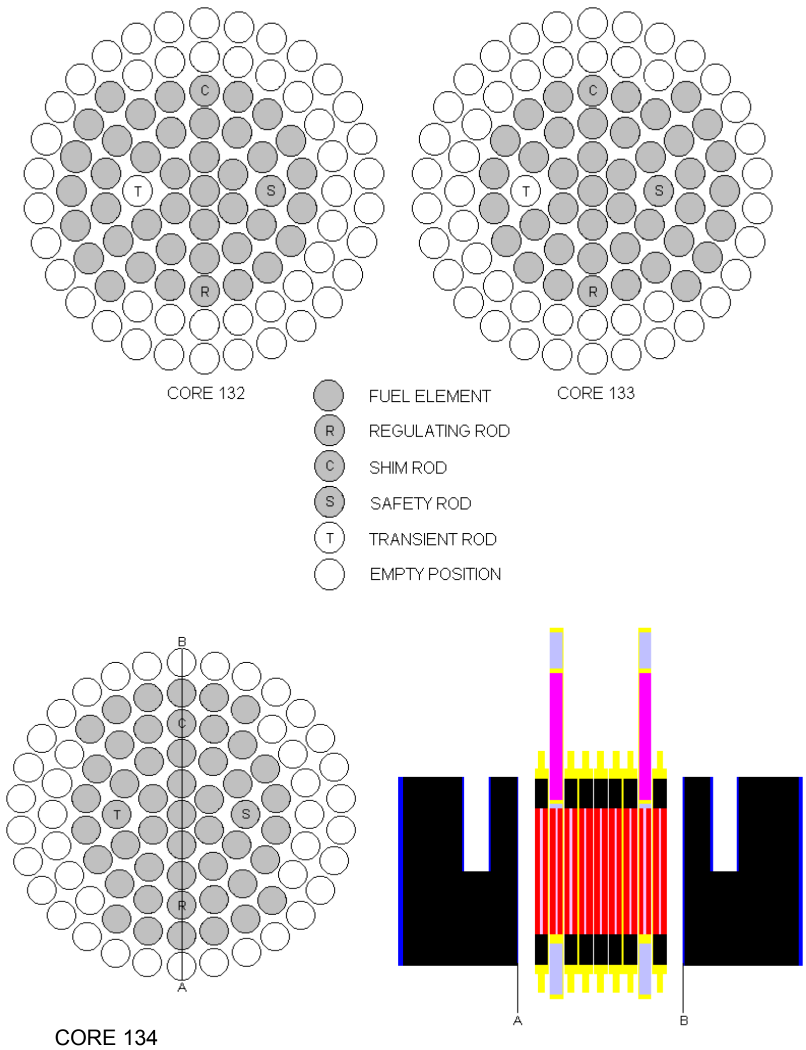


**Figure 1:** Configurations of core 132,133 and 134

In Monte Carlo simulation, material compositions of fuel rods are assumed to be identical. The material compositions of control rods are also assumed to be identical with each other and both are given in Table I. 44 and 238-group ENDF/B-V, 27-group ENDF/B-IV and 27-group burnup cross-section libraries were used for the criticality calculations. 44-group ENDF/B-V cross-section library was used for the control rod worth calculations.

**TABLE I.** Material Properties

| Material | Density (g/cm$^3$) | Element | Weight (%) |
|---|---|---|---|
| Fuel | 6.122 | $^{235}U$<br>$^{238}U$<br>$^{nat}Zr$<br>$^{1}H$ | 2.332<br>9.386<br>86.701<br>1.581 |
| Zirconium Rod | 6.49 | $^{nat}Zr$ | 1.0 |
| Graphite Reflector | Theoretical density<br>2.10<br>20% porosity 1.68 | $^{12}C$ | 1.0 |
| Absorber ($B_4C$) | 2.48 | $^{10}B$<br>$^{11}B$<br>$^{12}C$ | 13.690<br>64.588<br>21.722 |
| Stainless Steel Cladding (SS304) | 7.94 | $^{nat}Cr$<br>$^{55}Mn$<br>$^{nat}Fe$<br>$^{nat}Ni$<br>$^{nat}Si$<br>$^{12}C$<br>$^{31}P$ | 19.0<br>2.0<br>68.375<br>9.5<br>1.0<br>0.08<br>0.045 |

## 3 CRITICALITY SIMULATIONS

Criticality calculations of core configuration number 132, 133 and 134 were performed using different cross-section libraries and the results are given in Table II. For comparison, the simulation results obtained using KENOV.a with 44-group ENDF/B-V cross-section library, experimental and MCNP simulation results are given in Table III. The objective of doing such a calculation was to check the multi-group neutron cross-section libraries used in control rod worth simulations. Comparing the simulation and experimental results given in [3] and [1] with the results obtained using KENOV.a, 44-group ENDF/B-V library was selected to use in the simulation of rod insertion and rod exchange experiments.

**TABLE II**. $k_{eff}$ calculations with KenoV.a

| Group | 132 | 133 | 134 |
|---|---|---|---|
| 44group ENDF-V | 0.9993±0.0005 | 1.0026±0.0004 | 1.0202±0.0003 |
| 238group ENDF-V | 1.0035±0.0005 | 1.0065±0.0004 | 1.0244±0.0005 |
| 27group ENDF-IV | 0.9945±0.0004 | 0.9977±0.0004 | 1.0142±0.0004 |
| 27BurnupLibrary | 0.9935±0.0004 | 0.9964±0.0005 | 1.0147±0.0004 |

**TABLE III.** $k_{eff}$ of core configurations 132 and 133

| Configuration | Experimental | MCNP4A | KenoV.a |
|---|---|---|---|
| 132 | Not measured | 1.00102±0.00029 | 0.9993±0.0005 |
| 133 | 1.00310 | 1.00428±0.00028 | 1.0026±0.0004 |

As shown in Fig 2., Monte Carlo simulation results of full core shows that when all control rods are withdrawn, the fission density distribution was almost symmetric according to the plane which goes through the transient and safety rod. And the excess reactivity of the system was obtained to be ~2000 pcm using the effective neutron multiplication factor when all rods are withdrawn.

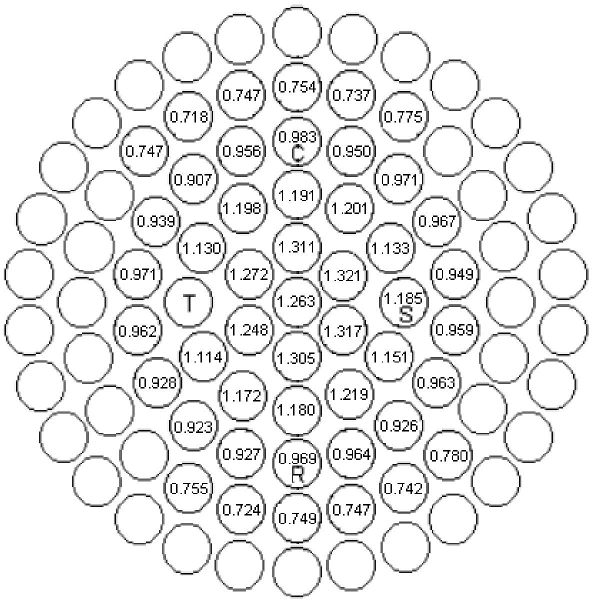


**Figure 2:** Fission density distribution of core configuration 134, all rods out

### 3.1 Control rod worth measurement using rod insertion

The rod worth measurements of regulating, shim and safety rod with fuel follower and transient rod without fuel follower were performed for core configuration number 134. Simulation and experimental results are given in Table IV.

**TABLE IV.** Control Rod worths by Rod Insertion Method

| Inserted (cm) | R (pcm) | | C (pcm) | | S (pcm) | | T (pcm) | |
|---|---|---|---|---|---|---|---|---|
| | Experiment | KenoV.a (±70) | Experiment | KenoV.a (±70) | Experiment | KenoV.a (±70) | Experiment | KenoV.a (±70) |
| 5 | 70 | 67 | 71 | 260 | 83 | 192 | 90 | 154 |
| 10 | 312 | 405 | 305 | 376 | 369 | 716 | 302 | 512 |
| 15 | 742 | 892 | 686 | 902 | 873 | 1265 | 667 | 970 |
| 20 | 1347 | 1393 | 1160 | 1344 | 1562 | 2100 | 1149 | 1423 |
| 25 | 2040 | 1790 | 1619 | 1760 | 2328 | 2898 | 1667 | 1920 |
| 30 | 2684 | 2211 | 1997 | 2110 | 3003 | 3431 | 2103 | 2261 |
| 35 | 3110 | 2372 | 2232 | 2341 | 3453 | 3637 | 2400 | 2392 |
| 38.1 | 3227 | 2331 | 2290 | 2311 | 3592 | 3606 | 2476 | 2493 |

The simulation results of core configuration 134 show that, since all the rods have identical material properties and core configuration is almost symmetric, control rod worth and regulating rod worth should be the same in the rod insertion method.

But as indicated in [2], there were some difficulties in the measurement of regulating rod worth. The position of the detector and regulating rod is close to each other; therefore local flux perturbations increased uncertainties in the measured values. Monte Carlo simulation results are consistent and neutron multiplication factors obtained from the simulation of regulating and control rod insertion experiments were almost same.

In Monte Carlo simulation, neutron multiplication factor and the shape of the fundamental mode in the presence of control rod were calculated. The simulation results give us more reliable information about the rod worth compared to the experimental results since the uncertainties related to the experimental devices and techniques were not included.

The results of core excess reactivity calculations for core configuration 134 using critical positions of control rods were given in Table V. The results are comparable with experimental data and simulation results obtained by using MCNP4A. In our Monte Carlo simulations via KENOV.a, core excess reactivity was determined to be 2163±40 pcm.

**TABLE V.** Core Excess Reactivity for Core 134

| Control Rod | Critical Position (cm) | Experimental (pcm) | MCNP4A (pcm) | KENOV.a (pcm) |
|---|---|---|---|---|
| Estimation from Control Rod Critical Position | | | | |
| Regulating | 28.4 | 2144(1±0.10) | 2037±50 | 2075±40 |
| Shim | 29.1 | 2108(1±0.10) | 2115±50 | 2031±40 |
| Safety | 21.6 | 1964(1±0.10) | 2132±50 | 2362±40 |
| Transient | 28.8 | 1872(1±0.10) | 2049±50 | 2185±40 |
| Average | | 2022(1±0.05) | 2083±50 | 2163±40 |

### 3.2 Control rod worth measurement using rod exchange technique

In the case of rod exchange, one of the control rods is inserted while the symmetric one is removed to compensate the negative reactivity insertion. The experimental data of integral rod worths as a function of control rod position for all control rods is given [1]. Experiment was performed using regulating rod with shim rod, and safety rod with transient rod.

**TABLE VI.** Control Rod Worths by Rod Exchange Method

| Inserted (cm) | **R** (pcm) | | **C** (pcm) | | **S** (pcm) | | **T** (pcm) | |
|---|---|---|---|---|---|---|---|---|
| | Experiment | KenoV.a (±120) | Experiment | KenoV.a (±120) | Experiment | KenoV.a (±120) | Experiment | KenoV.a (±120) |
| 5 | 107 | 202 | 110 | 223 | 145 | 170 | 94 | 280 |
| 10 | 396 | 719 | 394 | 650 | 499 | 762 | 303 | 687 |
| 15 | 836 | 1067 | 819 | 1142 | 1056 | 1524 | 651 | 1425 |
| 20 | 1366 | 2095 | 1323 | 1806 | 1749 | 2459 | 1106 | 1884 |
| 25 | 1869 | 2654 | 1805 | 2500 | 2272 | 3561 | 1583 | 2446 |
| 30 | 2213 | 2941 | 2139 | 2967 | 2718 | 3985 | 1934 | 2967 |
| 35 | 2423 | 3304 | 2318 | 3192 | 3164 | 4335 | 2142 | 3076 |
| 38.1 | 2552 | 3369 | 2430 | 3289 | 3440 | 4335 | 2270 | 3131 |

Using the same technique, Monte Carlo simulation of control rod worth calculations was performed. But, in the Monte Carlo simulation of rod exchange, simulations performed while removing the control rod in the presence of symmetric control rod fully inserted. First, the initial state of the system, mainly fundamental mode and eigenvalue corresponding to full insertion of one of the control elements were obtained. The simulation results give us the eigenvalue and corresponding power distribution in the presence of one of the fully inserted control element. The resulting core power profile is given in Fig.3 and 4.

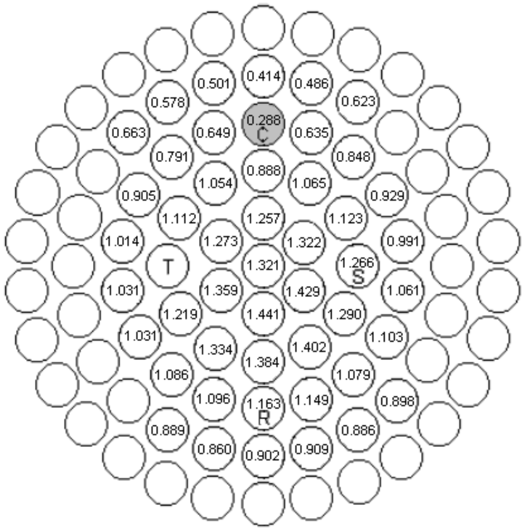


**Figure 3:** Power peaking factors of core 134 when shim rod is fully inserted

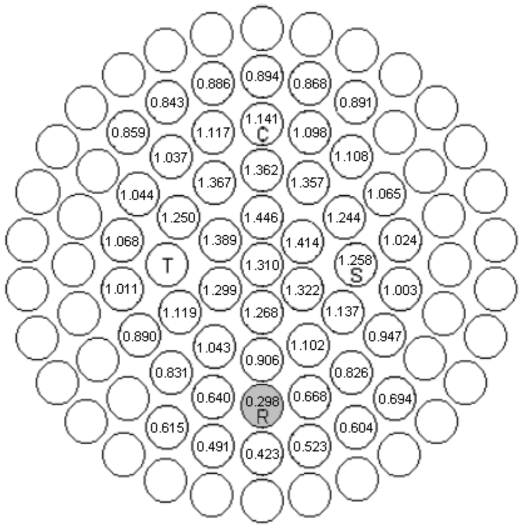


**Figure 4:** Power peaking factors of core 134 when regulating rod is fully inserted

Then, the rod worth calculations are performed for each control element. When shim rod was partially inserted, the shim rod worth was determined from the corresponding eigenvalue of the core in the presence of fully inserted regulating rod; same kind of simulation is performed for the regulating rod. For the safety and transient rods, similar Monte Carlo simulations were performed as in the case of shim and regulating rod.

The results of the simulations and experimental data are given in Table VI.

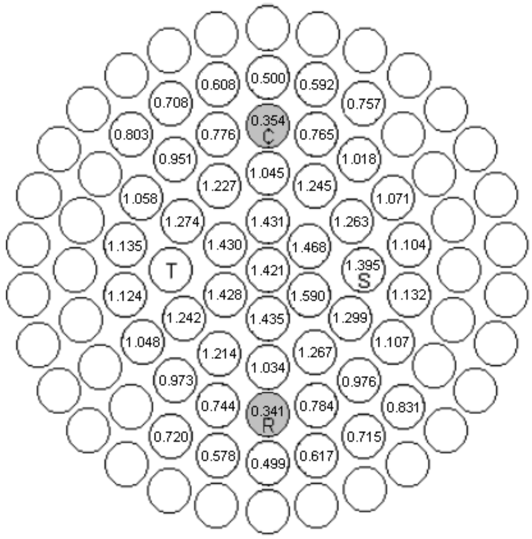


**Figure 5:** Power peaking factors of core 134 when both shim and regulating rods are fully inserted

## 4 CONCLUSION

Criticality and control rod worth experiments of Triga MARK II reactor were simulated using KENOV.a module of SCALE code system. In order to minimize the source of errors and approximations, detailed core geometry was used in the modelling.

Criticality experiments were simulated for three different core configurations. The results of KENOV.a with 44-group ENDF/B-V cross-section library were comparable with the experimental data and the simulation results of MCNP4a. Therefore, KENOV.a module of SCALE code system with 44-group ENDF/B-V cross-section library was used for the simulation of the rod worth experiments.

Two sets of experiments were used to evaluate the rod worths and were simulated by using KENOV.a. The simulation of rod insertion experiments was performed in two steps. The multiplication factor and power profile were obtained before the rod insertion and that value of the multiplication factor was used with the multiplication factor of the core when control rod was inserted to determine the rod worth. The simulation results were consistent with the experimental results within the error bars except for the regulating rod. The main reason of these deviations from experimental data was due to uncertainties in the experimental results. More detailed explanation of the measurement error is given in [2]. Our calculations are consistent, since the rod worth of the regulating rod and shim rod should be comparable with each other due to core symmetry.

Rod exchange simulations do not exactly correspond to the experimental setup. The simulation of the core was performed in the presence of fully inserted control rod to determine neutron multiplication factor. The symmetric control rod was inserted and the new multiplication factor was obtained from the simulation. These two simulation results were combined to determine rod worth values of the second control rod. In the experiments, one of the control rods is used to compensate excess core reactivity, while the measured control rod is withdrawn from the reactor core. The simulation overestimates the rod worths about 1000 pcm compared to the experimental data in the case of rod exchange method.

Since, the power profile before perturbation was much more flat compared to power profile used in the case of rod exchange method, the measured data and Monte Carlo simulation results are inconsistent. The main reason of this discrepancy is due to the model used in the Monte Carlo simulation of the rod exchange experiment. Our simulation results do not correspond to the experimental data of rod exchange.

However, these simulation results indicate that the power distribution and the shape play an important role in the determination of rod worths. Therefore, the results of rod worth measurement are strongly correlated with the core configuration and measurement technique used in the experiment.

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